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FINAL REPORT
Development of a Portable Multispectral
Thermal Infrared Camera

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Table of Contents

1. PROJECT SUMMARY

2. INSTRUMENT SPECIFICATIONS

3. INSTRUMENT DESIGN

3.1. Mechanical Design	5
3.2. Optical Design	9
3.3. Signal Processing	11
3.4. Control Computer	11
3.4.1. Hardware	11
3.4.2. Software	13
3.5. Video	14

4. ANALYSIS OF SYSTEM PERFORMANCE

4.1. Sensitivity	15
4.2. Software Development	17
4.2.1. Areas of Concern/Uncertainty	18
4.2.2. Unfinished Functions:	20
4.2.3. Description Of Ready-Made Algorithm Files:	21

5. RECOMMENDATIONS

1. PROJECT SUMMARY

The purpose of this research and development effort was to design and build a prototype instrument designated the "Thermal Infrared Multispectral Camera" (TIRC). The Phase II effort was a continuation of the Phase I feasibility study and preliminary design for such an instrument. The completed instrument designated AA465 has application in the field of geologic remote sensing and exploration.

The AA465 Thermal Infrared Camera (TIRC) System is a field-portable multispectral thermal infrared camera operating over the 8.0 - 13.0 μm wavelength range. Its primary function is to acquire two-dimensional thermal infrared images of user-selected scenes. Thermal infrared energy emitted by the scene is collected, dispersed into ten 0.5 μm wide channels, and then measured and recorded by the AA465 System. This multispectral information is presented in real time on a color display to be used by the operator to identify spectral and spatial variations in the scenes emissivity and/or irradiance. This fundamental instrument capability has a wide variety of commercial and research applications. While ideally suited for two-man operation in the field, the AA465 System can be transported and operated effectively by a single user. Functionally, the instrument operates as if it were a single exposure camera. System measurement sensitivity requirements dictate relatively long (several minutes) instrument exposure times. As such, the instrument is not suited for recording time-variant information.

The AA465 was fabricated, assembled, tested and documented during this Phase II work period. The detailed design and fabrication of the instrument was performed during the period of June 1989 to July 1990. The software development effort and instrument integration/test extended from July 1990 to February 1991. Software development included an operator interface/menu structure, instrument internal control functions, DSP image processing code and a display algorithm coding program. The instrument was delivered to NASA in March 1991.

Potential commercial and research uses for this instrument are in its primary application as a field geologists exploration tool. Other applications have been suggested but not investigated in depth. These are measurements of process control in commercial materials processing and quality control functions which require information on surface heterogeneity.



2. INSTRUMENT SPECIFICATIONS

MULTISPECTRAL PORTABLE THERMAL IR CAMERA

Spectral Range: 8-13 μm

Spectral Bands: 10: 0.5 μm wide each.

Field of View: 20° x 20°

Focus Range: 1 meter to infinity.

Spatial Resolution: 192 x 192 pixels (1 frame); 1.8 mrad IFOV.

Speed: One complete frame (of all bands)
plus references in 1.125 seconds.

Operating Time: ≥ 3 hours per battery charge.
 ≥ 3 hours LN₂ dewar hold time.

Measurement Range: 0°C to +50°C.

Output Dynamic Range: 12-bit.

Video Display: Liquid crystal color television screen.
Three-inch diagonal display area.
RS-170 compatible.

Data Storage: 1.4 Mbyte, 3.5 inch floppy diskette.
Capacity: 2 data runs per diskette.
Creates MS DOS compatible binary data files.

Packaging: Tripod mounted sensor head.
Backpack mounted, bipod supported electronics.
Total instrument one-person portable.



Internal references: One Controlled temperature reference;
One Uncontrolled ambient reference.
Each reference viewed once per frame.

Image Processing: Built-in digital signal processor (DSP) with the following capabilities.

- a. Radiometric power correction of the stored data file.
- b. Pixel/frame averaging to improve SNR.
- c. Operator defined algorithms to enhance displayed data. Algorithm may be sums and/or ratios of selected channels.
- d. Automatic ranging contrast stretch of the image display.
- e. Maximum frames per image = 1024.

Sensitivity: Single sample NETD varies from 3°C to 5°C depending on channel.
Multiple sample averaged NETD $\leq 0.2^\circ\text{C}$ for all channels.

Size: Sensor head - 8 in.H x 9W in. x 10 in.D; plus tripod.
Electronics - 30 in.H x 16 in.W x 8 in.D;
Packframe - 35 in.H x 16 in.W.

Weight: Total weight - 38 lbs. consisting of:
Sensor head - 12 lbs;
Electronics - 26 lbs.

Environment: Operating temperature: + 5°C to + 45°C.
Storage: -20°C to + 60°C.
Humidity (non-condensing): 10% - 90%.

Software:

- 1. Instrument control program.
- 2. DSP collection/processing program.
- 3. Display control program.

4. Algorithm coding program.
5. DR DOS 3.4

Operator interface: Menu on 4 in. x 9 in. LCD text/graphic display.
66 key membrane keyboard for input.

OUTPUT FILE DATA FORMAT

The output file consists of two groups of data. The first group is made up of header information consisting of at least 10 lines of ASCII text. Each line is separated by a cr,lf character. The second group consists of 552,960 bytes of binary data. This group is the averaged image data for each of the 10 channels for each pixel in the scene. The data is written on 3.5 in. MS-DOS compatible high density (1.4 MB) floppy disks, two data runs per disk.

TIRC Ver: 1.0	Line 1: format version ID.
FILE: image.dat	Line 2: original file name.
DATE: Mon Dec 17 14:40:10 1990	Line 3: date/time of file creation.
NOTES: Notes line.	Line 4: operators notes line.
SATCOUNTS: 0 0 0 0	Line 5: data saturation counts. Ref: Hi Low Scene: Hi Low
FRAMES: 0	Line 6: number of frames in sample
IMAGESZ: 552960	Line 7: number bytes of image data
FRM# WIN HOT AMB BCK	Line 8: heading for per frame information.
	Line 9: first line of per frame information.
	...
	Line (8 + FRAMES): End of per frame information.

```
#Binary Data begins
```

Line (8 + FRAMES + 1): start of image tag.

552960 bytes of BINARY DATA

Binary image data is 12 bit pixel values packed 2 pixels/3 bytes.

```

bit: 23 + + + + + 16 15 + + 12 11 + + 8 7 + + + + + 0
      |      msb ch10      |      lsn ch10 / msn ch9      |      lsb ch9      |

```

Where:

- msb = Most Significant Bit.
- lsn = Least Significant Nibble.
- msn = Most Significant Nibble.
- lsb = Least Significant Bit.

The data is written in pixel order starting with line 0 pixel 0 for channel 10, 9, 8, ... 1; then line 0 pixel 1 for channel 10, 9, 8, ... 1. This continues for each of the 192 pixels in line 0, and repeats for the 192 lines.

3. INSTRUMENT DESIGN

The following section describes the instrument design in terms of mechanical, optical, electrical, and software.

3.1. Mechanical Design

To maintain as small a package as possible, several alternative concepts for implementing the movable reference mirror were investigated. The design approach selected uses a solenoid actuated pivoting mirror, to place the references into the detector field of view during the retrace of the slow scanning mirror. This occurs once each frame.

Polygon Mirror Drive System

The twelve facet polygon scan mirror is driven by a motor with a friction wheel riding on the mirror inside radius. The scan mirror rotates at 960 rpm giving 11,520 scans per minute (192 scans per second). Mounted on the polygon mirror drive axis is the worm of a 18:1 worm gear set driving the shaft on axis. This shaft drives the shaft through a 1:1 gear ratio 90° helical gear set. This shaft is rotating at 53.3 RPM or 1.125 seconds per

revolution. Mounted on this shaft are the cam for actuating the slow mirror and a second 1:1, 90° helical gear set. The slow mirror, rotating about the axis scans the width of the polygon mirror at a rate of one scan per second. The scan occurs during 300° of cam rotation with the retrace occurring during the remaining 60°.

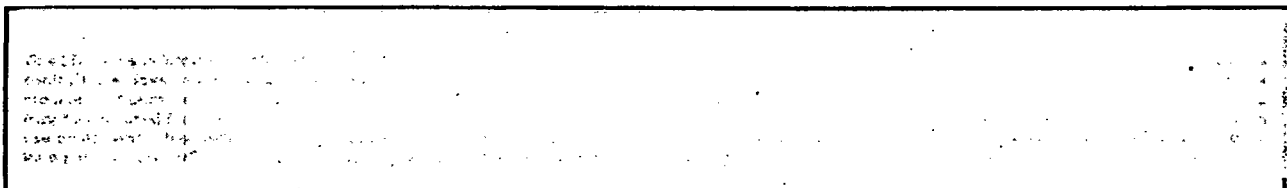
A mechanical layout of the thermal camera sensor head was developed on a 3-D CAD system (ANVIL 5000). Use of the 3-D design system aided selection of the best location and orientation of the various components to yield a compact package with minimal hardware clearance and no blockage of the optical path. The enclosure window size was determined using the rotation and mirror features of the 3-D design system to develop the outer limits of the scan rays at the intersection with the enclosure surface. The 3-D CAD system also eased the design of the grating mount and retaining mechanism which are oriented at complex angles from the normal viewing planes of a 2-D drawing system.

The general design approach was to develop separate modules of functionally related components. This resulted in a sensor head package of five independent modules plus a base plate and support structure. The individual modules are: 1) Optics; 2) Slow Mirror Drive; 3) Deviating Mirrors; 4) Polygon Drive and 5) Enclosure.

Optics Module

The primary lens is located in a separate housing. Alignment with the optical system axis is achieved with two shafts supporting the primary lens housing which ride in two sets of linear bearings. A motor driven linear actuator is used to move the lens to the desired focus position. The field stop and collimating lens are secured by retainers at fixed locations in the main optics housing. The grating position is determined by two orthogonal surfaces machined in the main optics housing. The grating retainer contains a leaf spring which maintains the grating against one of the surfaces as the clamps are tightened, seating the grating against the second surface.

The system image position adjustments are made by moving the image lens set with respect to the detector location. The image lens set (three elements) is located in a separate housing containing a dovetail slide. A screw drive adjusts the lens housing position normal to the optical axis. The lens housing dovetail has a mating slide in one leg of a L-shaped fixture with a second dovetail slide on the other leg. The second slide provides for focus adjustment of the image lens set. The mating piece to the focus slide



is a double dovetail oriented at right angles. One side of the double dovetail mates with the focus slide in the L fixture and the other dovetail mates with a groove in the main optics housing. This third slide provides for adjustment normal to the optical axis. All adjustments are made with fine thread screw drives and independently locked with two screws per adjustment axis.

A surface of the optical module housing is used as a mounting base for the reference source by the addition of a small bracket. The primary lens focus actuator is also fixed to the optical housing with a small bracket. The complete optics module is secured to the base plate on a set of stand-off mounts.

Slow Mirror Drive Module

The purpose of this assembly is to provide a one second scan of the 20° scene in a plane normal to the polygon scan. The polygon and slow mirror are coupled by two series gear sets with a total speed reduction of 18:1. With the polygon rotating at 960 RPM, the cam driving the mirror cycle rotates at 1.125 seconds per revolution. The cam, pushing a follower attached to the slow mirror, is cut to provide a uniform scan rate over the scene at 20° per second. A transition period of 0.125 seconds is used to return the slow mirror to its start position.

The Slow Mirror Drive Module contains the gear of a worm gear set (the worm is attached to the polygon shaft), main drive shaft, a right angle helical gear set, a cam, support bearings, cam/gear shaft and the slow mirror assembly. To assure the location and maintenance of the positions of the components they are designed into a single machined housing.

The 18:1 speed reduction is achieved with a 15:1 ratio worm gear set and a 1.2:1 helical gear set in series. The worm gear drives the main shaft at 64 RPM which has a 25 tooth helical gear on the output end. The cam shaft has a 30 tooth mating helical gear resulting in a cam speed of $53\frac{1}{3}$ RPM, or 1.125 seconds per revolution.

The slow mirror assembly consists of the mirror, pivot shaft, support housing with bearings and cam follower components. A torsion spring acting on the cam follower arm maintains the follower in contact with the cam.

Optical System Assembly
Drawing No. 100-100000-001
Part No. 100-100000-001
Rev. 100-100000-001
Date 100-100000-001

A circular disk with one hole (slot) at its periphery is mounted on the shaft with the cam. An optical sensor detects the slot once per cam revolution providing a control signal to the timing circuits. This signal together with a once-per-revolution signal from the polygon encoder determine the start of each frame.

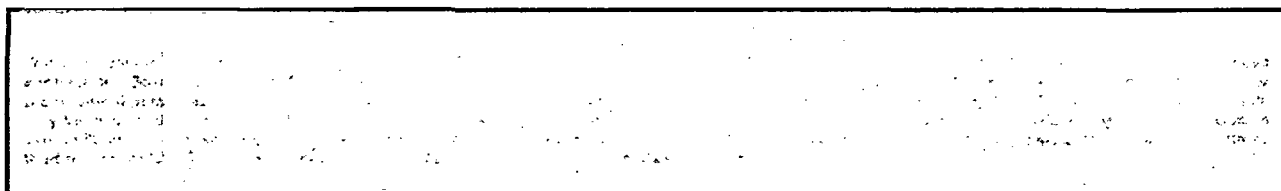
Deviating Mirror Module

Two mirrors are contained in the deviating mirror module. The primary mirror, fixed to the supporting mount, diverts the beam from the scanning mirrors into the spectrometer optics. The second mirror is attached to a rotary solenoid. The solenoid, which is secured to the module mount, rotates the second deviating mirror into the optical path during the 0.125 seconds of slow mirror retrace. This places the two reference sources into the sensor field of view sequentially. The total time allotted for the mirror transit and pause for reference sampling is 0.125 seconds. The detailed design of this mirror emphasized minimizing its mass in order to reduce transit time and power consumption. The rotary solenoid has a projected life of 50 million cycles without lubrication. At the proposed cycle rate this solenoid life is nearly 14,000 hours of system operation. This module also has an opto-interrupter device to provide a signal confirming the position of the mirror attached to the solenoid.

Polygon Drive Module

The polygon scan mirror is suspended on a shaft which is supported by bearings in the module mounting plate and bearing housing assembly. The slow mirror drive worm is pinned to the shaft and reacts against the lower bearing. The encoder is also located on the polygon shaft and is supported by the upper surface of the bearing housing. The polygon drive motor is precisely located on the plate to engage the inner surface of the polygon with the friction wheel. The ambient reference source, the C-shaped cup located below the polygon, also functions as a hub in securing the polygon to the shaft.

The module mounting plate is machined for minimal weight while maintaining the necessary component support function. The module mounting plate is supported by four legs secured to the scan head base plate.



Enclosure Module

The scan head enclosure consists of a vacuum formed thermoplastic housing, window assembly with protective cover. The enclosure slides over the scan head components and is secured to the base plate. A semi-sealed opening is provided in the top for the dewar fill port. Liquid nitrogen boil-off gas from the dewar is vented into the enclosure when the dewar cap is installed.

General Assembly

Four of the five modules attach to the base plate directly or with standoffs or support legs. The dewar is also secured directly to the base plate. The Slow Mirror Drive Module is mounted on the Polygon Drive Module plate. The base plate is machined for weight reduction and has a provision for standard tripod mounting.

Two electronic assemblies are located within the scan head enclosure. One assembly (preamplifiers) is located above the polygon module in the region of the dewar. The second assembly is mounted to the scan head base plate below the polygon. The I/O connector is located on the base plate passing through the bottom of the enclosure.

3.2. Optical Design

A significant change from the original concept of the instrument is inclusion of a second blackbody reference into the optical path of the sensors. The decision to add this reference was reached while analyzing the data processing tasks required to obtain useful and consistent information for the real-time image display. The second reference, although its temperature is not controlled, permits scaling and offset adjustments to be made to each channel in a repeatable process. The basic arrangement of the sensor head is not altered by this addition. Each reference is viewed once per frame. The penalty for adding the second reference is a small increase in the size and mechanical complexity of the sensor head.

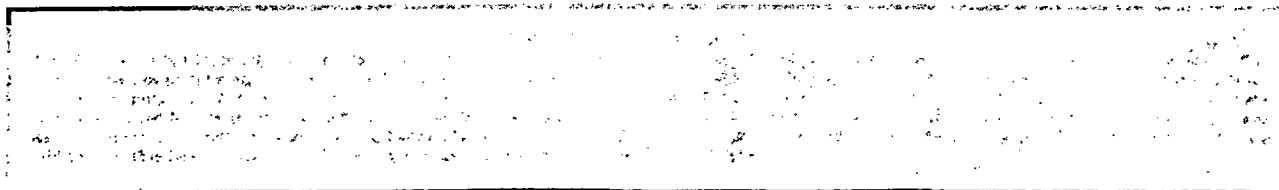
All lens elements and assemblies have been designed to provide diffraction limited performance. The imaging portion of the optical system consists of a single element germanium primary lens, a single element germanium collimating lens, and a three element, color-corrected imaging lens. A diffraction grating and detector array/dewar

assembly completes the optical system. The individual detector element size has been increased from the preliminary design value of .002 in. square to .004 in. square. This change is necessary due to manufacturing limitations governing the minimum spacing required between adjacent detector elements. The minimum achievable physical spacing between adjacent detector elements is approximately .0005 in. It was decided that the inactive to active detector area ratio ($.0005/.002 = .25$) was too high. The change to a .004 in. square detector element reduces this ratio to 0.125. The increased detector size contributes to the poorer than expected single frame SNR performance of the instrument.

One of the major issues governing the final lens design was the estimated effect of diffraction on system performance. One form of diffraction which effects the performance of the instrument is plane wave diffraction from a circular aperture. This type of diffraction occurs at both the primary and imaging lens clear apertures. At the primary lens this type of diffraction has the effect of limiting (degrading) the spatial resolution of the instrument. At the imaging lens it has the effect of limiting (degrading) the spectral resolution and, to a lesser extent, the SNR performance of the instrument.

A computer analysis of plane wave diffraction was conducted. The results of this analysis have allowed us to bound the magnitude of degradation introduced by the diffraction occurring at the primary lens. Using the final primary lens and field stop specifications, the analysis predicts that between 70-85% of all of the energy which should be imaged through the system field stop by the primary lens actually passes through. The remainder of the energy (15-30%) is obscured by the field stop. This effectively reduces the spatial resolution of the instrument. Based on previous experience, our estimate of 70-85% field stop throughput should ensure satisfactory instrument spatial resolution. Since the f-number of the instruments imaging lens is smaller than the primary lens, the magnitude of plane wave diffraction introduced by the imaging lens should be less than or equal to that occurring at the primary lens. As such we anticipate satisfactory instrument spectral resolution performance as well.

An additional diffraction phenomenon occurs at the instruments field stop. This type of diffraction is not accurately predicted using plane wave diffraction theory since it results from the interaction of a converging spherical wave front and a square aperture. The presence of this diffraction phenomenon has the potential of affecting the instruments SNR performance. SNR performance would be degraded if a significant portion of the



energy which passes through the instruments field stop is diffracted outside the clear aperture of the collimating lens. A computer program was written in order to quantify this phenomenon. Results of this analysis indicate that the percentage of energy which is diffracted outside the clear aperture of the collimating lens is small (effectively zero).

3.3. Signal Processing

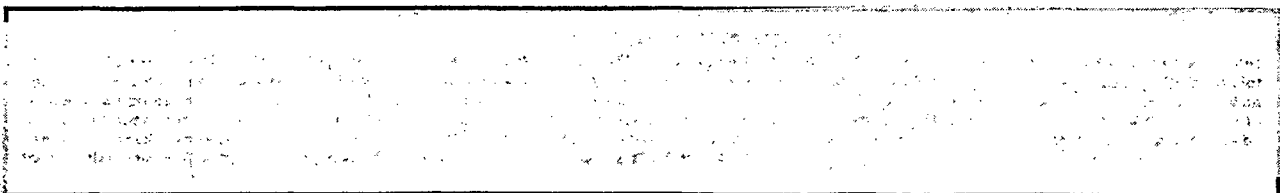
The signal processing effort focused on two areas: reference definition and image processing. Given two references of known temperatures the image processing software can radiometrically correct each spectral pixel in the scene. Two types of radiometric correction were examined: power and temperature. Power correction involves the use of Planck's Law to calculate the power contained in the spectral band of each detector; errors associated with power correction are limited by noises in the system. Temperature correction linearizes the detector readings to arrive at an "effective" temperature for each spectral pixel. Errors caused by path differences between the references and the scene pixels will be present for both types of radiometric correction. Path differences exist due to the references being internal to the instrument, and one additional mirror surface required to be in the path of the scene energy. Power radiometric correction was selected as the best method for this instrument.

3.4. Control Computer

The control computer oversees all TIRC processes. The following describes the control computer from a system integration perspective concentrating on its supervision of these processes. Its function in the radiometric correction and calibration loop, and the data flow to floppy disk will be covered separately.

3.4.1. Hardware

The control computer hardware is composed of three major sections: digital inputs, digital outputs, and analog inputs. The digital inputs monitor the status of the system, the digital outputs control when events occur, and the analog inputs monitor and indirectly control the thermal references.



Digital inputs

The control computer has four digital inputs: End-of-Reference (EOR), End-Of-Image (EOI), data out of range, and mirror fault. The EOR input indicates that the last reference pixel has been read. The EOI input indicates that the last image pixel has been read. Data out of range indicates that at least one scene pixel or reference pixel signal amplitude is beyond the range of the A/D converter circuits. This signal also contains the direction (hi or lo) of the out of range condition. Mirror fault indicates that the reference mirror has not achieved the correct position for reading the references, or that it has not retracted fully for reading the scene data. The EOR and EOI inputs are processed as hardware interrupts from the DSP to the PC, the other inputs are presented to the operator on the display. Reference out of range data is recorded onto the floppy when the data is saved.

Digital Outputs

The control computer has eight digital outputs: Scan-Motor-On/Off, Conversion-On/Off, Heater-On/Off, Display-On/Off, Offset, and three outputs to control the focus motor. The Scan-Motor-On/Off enables the hardware motor speed controller. The Conversion-On/Off output enables the data collection process, which starts with the next reference cycle. The Display-On/Off output enables power to the color video display screen. The Heater-On/Off output enables the reference heater. The temperature of the heated reference is controlled by a software pulse width modulation algorithm. Offset is an operator selected DC voltage that is applied to each channel signal prior to A/D conversion. The focus motor is controlled by three outputs: Focus-On/Off, Focus-Direction, and Focus-Step. The Focus-On/Off output enables power to the stepper motor that adjusts the lens focus. The Focus-Direction output selects the direction the stepper motor moves when the step signal occurs. The Focus-Step output drives the motor one step in the direction selected by the direction output. These digital outputs are accessed through the control computer I/O space.

Analog Inputs

The analog inputs monitor the output of the thermistors on the hot and cold references, the input window temperature, and the temperature of the backpack. The analog thermistor signals are amplified then processed by an analog to digital converter that is accessed through the control computer I/O space. The analog inputs are sampled by an interrupt

service routine that also maintains the Heater-On/Off output. Each of these sensors is sampled once per frame. This data is accumulated and written to the floppy disk when the data is saved.

3.4.2. Software

The control computer software is composed of four major sections: user interface, instrument control, algorithm coding, and radiometric correction. The user interface and instrument control sections are localized to the interaction with the user and peripherals controlled by the control computer. The algorithm coding and radiometric correction sections support the operation of the DSP.

User Interface

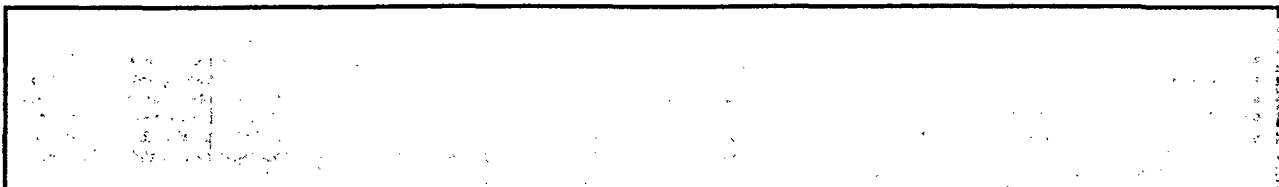
The user interface is a menu system which accepts operator commands and displays parameters and system status. The menu groups the commands into four sub menus for control of data collection, focus/setup, miscellaneous utilities and hardware diagnostics. A command menu bar provides the operator picks for setting parameters and commanding system functions. Each pick causes the program to call a control subroutine to implement the action. Background polling checks each subsystem and displays the current status on the screen. After a process has been selected and the parameters selected the user interface passes control to that process.

Instrument control

The control computer interfaces with five hardware subsystems. They are: Conversion Timing Generator; Mirror Motor drive; Video Display; Reference Controller; and DSP.

The interfaces for the timing generator, mirror motor and video display allow ON/OFF control of these hardware subsystems, and reading the current status.

The reference control module provides input of the ambient and hot reference temperatures and controls the hot reference temperature. The control routine uses the computer's built-in serial port to generate control interrupts every 10ms. On each interrupt it reads the reference temperatures and calls the hot reference PDI control routine. This routine computes the control voltage, then converts this to a value that is written to the serial port. The number of bits on determines the duty cycle of the waveform. The heater



duty cycle is adjusted to maintain the hot reference at a user selected temperature difference above the cold (or passive) reference. The system also uses this interrupt to test the state of the timing controller and compute the radiometric correction between frames.

The DSP interface provides downloading programs and parameters to the DSP, sending commands, transferring images, reading status, loading DSP object files, and setting the radiometric correction. During the control interrupt, at the end of a frame the control computer calculates the radiometric correction for the DSP. It uses the reference temperatures read by the reference control module and the reference values read by each detector and supplied by the DSP. It then sends the corrections to the DSP before the start of scene data processing.

The digital inputs are interpreted on a periodic basis. With the exception of the heater control, the digital outputs change as a result of the operators request. The analog inputs from the thermistors and the heater control bits are sampled by an interrupt service routine that runs about 100 times per second. The interrupt service routine reads the thermistor values, uses a look-up table to translate the value into a temperature, and adjusts the duty cycle of the heater.

3.5. Video

The video section of the instrument takes the output from the DSP algorithm, converts the data into a form that the display can use, and buffers it for refreshing the display. The video section also performs a contrast stretch on the data so that the information presented always uses the full dynamic range of the display circuits.

Interface: DSP - Video Display

The DSP will send four bytes to the Display Processor for each displayed pixel. This data is comprised of a command byte, followed by bytes representing the Red, Green, and Blue value of each pixel. The Display Processor generates a new pixel value from this information, by using a lookup table for each of the components. This lookup table performs a contrast stretch of the data to enhance and normalize the display. Each component (R, G, & B) can have 16 possible values. The lookup table is regenerated by



the Display Processor between each frame using the max/min information sent to it by the DSP.

4. ANALYSIS OF SYSTEM PERFORMANCE

This section will compare the design goals of the program development with the performance that was actually achieved with the delivered instrument. Where there are deviations, a recommended course of corrective action or area for investigation will be outlined.

4.1. Sensitivity

The single sample sensitivity performance of the system is greater than the design goal. There are several contributors to this degradation detailed by the following list.

1. SNR estimates.

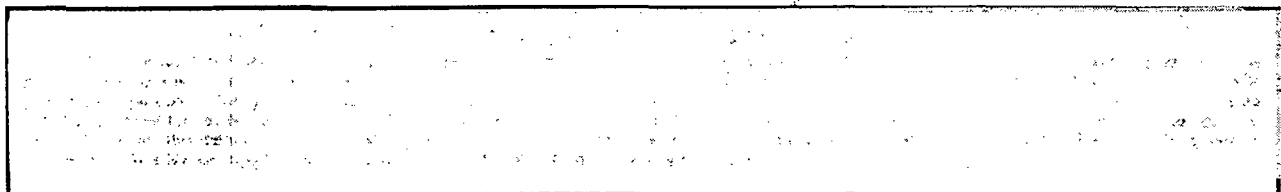
The actual efficiency of procured optical components, and detector array performance were less than assumed in the calculation of SNR. The image blur size at the detector is a significant fraction of the detector area, and this was not accounted for in the calculations. The physical gap between adjacent detector elements reduces the effective detector area.

A method to precisely measure the single sample SNR has not been developed, but is estimated to be approximately 5°C. There is no suggested course of corrective action for this component of the deviation.

2. Multiple frame averaging.

The method of using multiple samples of the same scene pixel, and improving the overall SNR by averaging these samples is based on the assumption that all of the noise terms are random. In such a case, the SNR will be increased by the square root of the number of samples that are averaged.

In the real instrument there is some non-random noise, from both electrical and mechanical sources. These coherent noise sources effectively place an upper limit on the number of frames that can be averaged before any further SNR improvement



is obtained. The upper limit of frames that can be averaged before this point is reached lies between 10 and 100.

The magnitude of the coherent noise terms must be reduced if the effectiveness of the averaging technique is to be increased by averaging more frames. The dominant electrical source of the coherent noise are from two sources: 1) The power supplies for the sensor preamplifiers. 2) Clock feed through at the switched capacitor low pass filters.

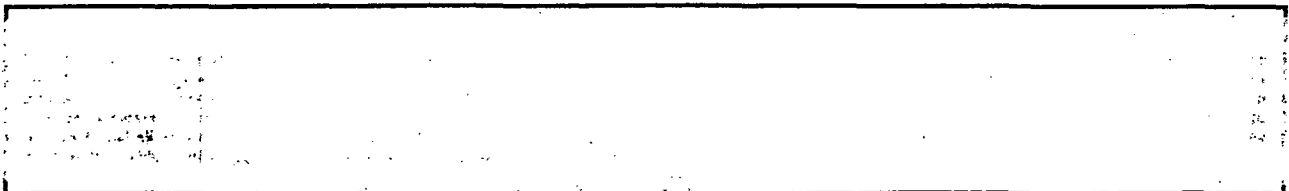
Another coherent noise has been observed in imagery collected and displayed by the instrument. This noise appears as dark/light horizontal bands across the image. The exact source of this noise has not been located; however, it is believed to originate in the mechanical system that drives the mirrors.

3. Low pass filter cut-off frequency.

A low pass anti-aliasing filter has been implemented for each channel using a "switched capacitor" filter circuit. The frequency of the clock to this circuit sets the -3dB frequency of these filters. The source of this clock is the control computer within the instrument. This signal (14.3 MHz) is divided by 4 to obtain 3.5 MHz which is the (clock) input to the filter circuit. A 3.5 MHz clock produces an upper band edge of 71.5 KHz. This band edge is approximately 15 KHz higher than theoretically required to meet system spatial resolution.

To lower this band edge the clock frequency must be reduced by using an alternate source for the clock. This can be accomplished by replacing the control computer clock input to the filters with an oscillator circuit of the correct frequency. Lowering this band edge will reduce the noise bandwidth proportionally, increasing the SNR by the square root of the ratio, or approximately 12%.

This modification is a relatively simple change to the system, with a well defined pay back.



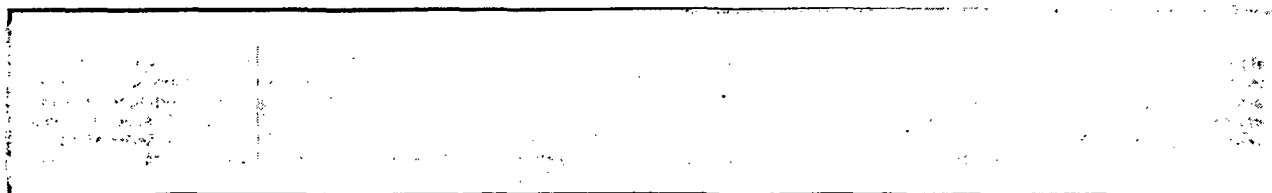
4.2. Software Development

This section summarizes the known problems, areas of uncertainty, unfinished functions, and embedded testing and status reporting capabilities of the Thermal IR Camera instrument, focusing mainly on the Motorola DSP software. It also describes some of the ready-made algorithms supplied at delivery.

- A) Display screen shows stable noise features; "stable" meaning feature is in the data being sent to the screen for a minimum of 3 frames. These features include 3 "black holes" in lines 180 to 191 (counting from 0), random single pixel bright noise, and bright lines of varying length and random position. Sometimes these features appear in one frame, begin to be averaged out, then reappear "refreshed" in the same position in a later frame.

The 3 black holes may have a different cause from the other features, since they always appear in the same general locations (although the sizes of the holes vary with time), and have been observed to come and go with fake (hard-coded) A/D data. Data in lines 180 — 191 all lie in the next to last bank of external X memory; repetitive ram testing of this bank is recommended to spot a possible "soft" ram error.

- B) The temperature per channel graph on the text screen changes enormously from frame to frame. Originally thought to be correlated with data out-of-range of good radiometric correction, but still occurs when corrected data is apparently good (i.e., between 0 — 4095). Further investigation needed before solution can be recommended.
- C) Objects on screen with vertical edges appear to be "saw-toothed"; the scene seems to have 12 to 16 of these "teeth", evenly spaced, from top to bottom, as if scene sampling is not beginning precisely at the same point in each scan line. May be an optical encoder centering or alignment problem.
- D) MIRROR on text screen flashes when head is tilted at some angles. The return spring within the solenoid is not strong enough to retract the mirror quickly for all operating attitudes. No solution recommended except reduced range of operating attitudes.



- E) System crashes with a "5X"-type error, waiting for DSP to send end-of-reference (EOR) or end-of-image (EOI); denotes DSP and rest of hardware are out-of-sync. Usually corrected by changing to a simpler (and faster) user-algorithm. See discussion below.
- G) Temperature graph on text screen overflows graph boundaries, clobbers "Temperature/Chan" annotation on bottom of graph. Solution is to enhance bounds checking in PC graph output.

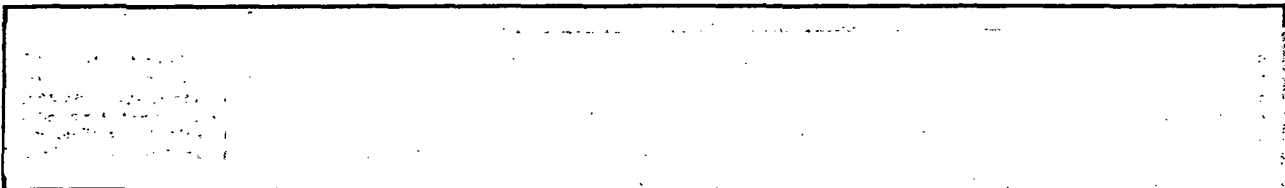
4.2.1. Areas of Concern/Uncertainty

A) Radiometric Correction

This correction has been exercised by a test program which predicts the A/D input used as a function of input reference temperatures and reference pixel values; 20 —> 30 numbers were tested. As another test, fake A/D values were collected for one frame, and the resulting averaged/corrected numbers were examined in memory, then compared with hand-calculated numbers based on the observed scale factors and offsets. Confidence in the radiometric correction would be higher if these tests could be repeated more often with different A/D input data, reference temperatures, and mean reference reading differences.

More generally, the domains of the radiometric correction input data (temperature of the references, difference in averaged reference readings for each channel, and A/D data) which produce meaningful output data ($0 \rightarrow 4095 \text{ uWatts/cm}^2$) are not well known. It appears negative corrected data can be generated in some circumstances. Too small a difference in reference readings for one channel can yield an enormous power value for that channel.

Effects of negative corrected (power) data on the cumulative downloaded average data are probably small if confined to a small fraction of the collected frames; they will degrade the display, depending on the user algorithm. However, a large enough power value, occurring in even one frame, can overwhelm the sum of values for that channel, even if the sum is formed from a large number of frames. Wildly huge power values will make the display difficult to interpret (because the software displays only the least significant bits), and will make that particular channels data in the downloaded image totally meaningless.



Depending on the user-algorithm, it may be possible for bad data to occur without the user being aware of it. Adding a smart front end to the ENHANCE code, or a smart limit checking subroutine before calling ENHANCE (if there is execution time available for this - see below) could either signal the operator (through values in DATA_STATUS) of the presence of bad corrected data, or even "fix" the values in some to-be-determined way.

Efforts to improve the robustness of the radiometric correction, and out-of-bounds number handling will probably be most efficient when implemented in the PC software, rather than the heavily time-loaded DSP assembly language.

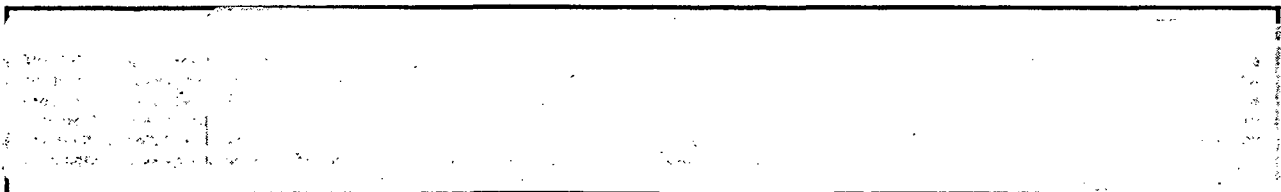
B) Display Routines/Execution Time Issues:

The sequence of display-related events which happen every scene pixel is:

- 1) Use averaged/corrected values, put through user-algorithm, re-scale, get red, green, and blue (RGB) enhanced values.
- 2) Limit the enhance values to 0 - 511.
- 3) Contrast stretch each RGB value by looking up its value in an LUT for that color, get RGB display values 0 - 15.
- 4) Pack the red, green, and blue display values into one word, output it to the video PAL.
- 5) Accumulate the RGB enhanced values, and the values squared ($\text{sum and sum } ()^{**2}$) for next frames LUT's.

There is a severe time constraint on these routines. At present it appears that a non-simple ENHANCE (user-algorithm) routine will take so much time that the system will get behind and will crash (a "5X" error, like PC was waiting too long for either EOR or EOI).

This display loop can be further optimized. A small savings can be achieved by merging some of the subroutines to avoid extra reads/stores, and time-consuming subroutine jumping (JSR's and RTS's). Another small savings will occur if counting out-of-bounds ENHANCE output values (shown in part of the DATA_STATUS word), were com-



mented out. It is estimated that together these savings would amount to less than 10% of the present execution time of these routines.

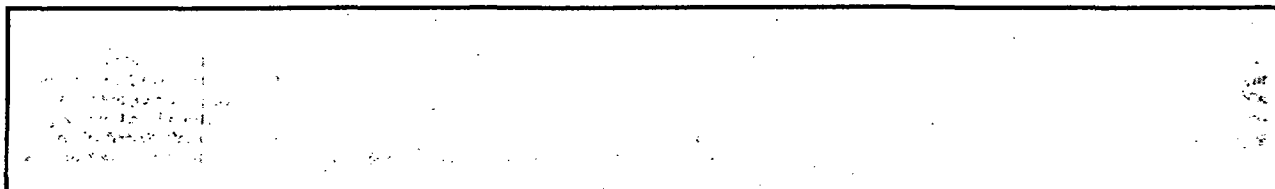
Further time optimization might be achieved by utilizing the existing, or an expanded divisor table, rather than using DIV instructions, in the ENHANCE user-algorithm when ratios are desired. This method is already used for fast divides when making the LUT's. An optimized version of this code might be significantly faster than using repetitive DIV iterations, even when the bounds checking is included. The method is worth exploring if ratios are essential in more than one ENHANCE color and the algorithms cause the DSP to get behind.

4.2.2. Unfinished Functions:

- A) **DISPLAY_RAM.** This function sends the current contents of external (image) memory to the display after rebuilding the LUT's using a new value of ENHANCE (the contrast number entered in menu 1), and recalculated mean and standard deviation values. Useful for users to evaluate different display algorithms on the same data. Code is written and exists in DSP7.ASM, an untested version.
- B) **UPLOAD_IMAGE.** This function uploads a previously saved image from floppy to external memory, then displays it, following the procedure outlined above in DISPLAY_RAM. A straight-forward routine, not yet written.
- C) **COMPUTE_FOCUS.** As originally designed, this function would compute some mathematical quantity sensitive to spatial frequency using the center 10x10 window, and download this number to the PC. This has not been coded.

A quick fix, useful only for very bright, high-contrast scenes, was implemented which just turns frame averaging off: the display shows only the latest frames data. Currently implemented only in the algorithm named DSPFOCUS.

- D) **COMPUTE_NETD.** This routine would use the reference readings to compute an NETD for each channel of the instrument for a user specified number of frames. Designed, but not coded.



4.2.3. Description Of Ready-Made Algorithm Files:

DSP1 - Puts channel 1 —> red, zero —> green & blue.

DSP2 - Puts channel 2 —> red, zero —> green & blue.

DSP3 - Puts channel 3 —> red, zero —> green & blue.

DSP4 - Puts channel 4 —> red, zero —> green & blue.

DSP5 - Puts channel 5 —> red, zero —> green & blue.

DSP6 - Puts channel 6 —> red, zero —> green & blue.

DSP7 - Puts channel 7 —> red, zero —> green & blue.

DSP8 - Puts channel 8 —> red, zero —> green & blue.

DSP9 - Puts channel 9 —> red, zero —> green & blue.

DSP10 - Puts channel 10 —> red, zero —> green & blue.

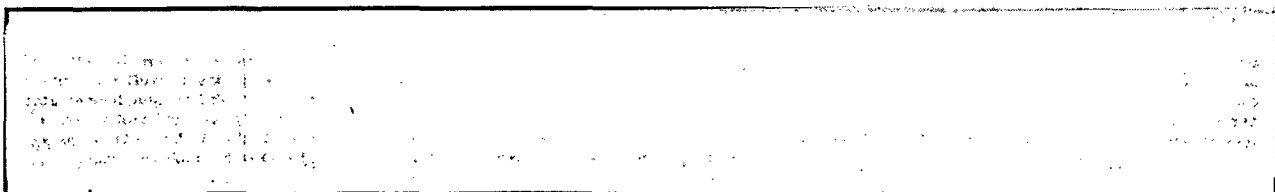
DSP123 - Puts channel 1 —> red
 2 —> green
 3 —> blue.

DSP456 - Puts channel 4 —> red
 5 —> green
 6 —> blue.

DSP8910 - Puts channel 8 —> red
 9 —> green
 10 —> blue.

DSPSUM- Puts average of all 10 channels —> red, green, blue.

DSPGROUP - Default algorithm in DSP.LOD.
 Puts average of channels 1, 2, 3 —> red,



Puts average of channels 4, 5, 6 - > green,
Puts average of channels 7, 8, 9, 10 - > blue.

DSPFOCUS - Turns averaging off.

5. RECOMMENDATIONS

Although functional as delivered, the TIRC instrument needs to be more thoroughly characterized to improve the value of its output. A major step toward this goal will occur as soon as JPL is able to read the data files created by the instrument into their image processing system. At the present time there is no alternative way to examine the instrument output in the required detail.

Although the instrument has not been completely characterized in the laboratory, the following points are known to need further investigation or improvement. Additional information about each of these points is contained within the text of this report.

1. The single sample SNR should be increased.
2. The unimplemented operating software features should be written and tested.
3. The DSP code should be further optimized for speed so that more powerful algorithms may be used.
4. The radiometric correction process should be exercised and examined thoroughly.
5. The total range of the Planck look-up tables for the reference sources should be increased.
6. The instrument should be tested in field operations.